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Knoll, A. and Walter, F.

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Neurorobotics – a Unique Opportunity for Ground Breaking Research

Alois Knoll and Florian Walter

Chair of Robotics, Artificial Intelligence and Real-Time Systems
Department of Informatics
Technical University of Munich

knoll@in.tum.de, walter@in.tum.de

Neurorobotics is an emerging transdisciplinary field of research at the interface between neuro- and cognitive sciences, artificial intelligence and robotics [1, 2]. It has enormous potential to cross-fertilise these areas and at the same time enable the construction of new classes of cognitively oriented robots. These are much closer to the human world of perception and action than all systems available thus far. In the medium to long term, this will open up new opportunities for German industry to assume a leading role in a newly emerging market.

1 Design and Functions of Neuro-Robots

A neuro-robot is a robot whose perceptual apparatus and control are based on an (as accurate as possible) model of the processes in the biological model. Such a robot can either be representational, i.e. classically constructed as a multi-axis mechanism made of metal or plastic, or it can only exist as a simulation in a virtual environment that has been reproduced with maximum accuracy [3]. In both cases, the body can be close to the biological model (e.g. a four-by-one walking robot in the shape of a dog) [4] or it can be oriented towards a specific task (such as the well-known industrial robots in automobile factories).

Obviously, the success of neuro-robots in practice depends critically on the fact that the brain models contributed by neuroscience and the simulations based on them are as accurate as possible, at least with regard to the investigated task. But what makes them unique is that they can also be run on computers in real time. The term "computer" is broadly defined here: classical digital computers can be used to implement the necessary processes in the robot, but digital or analog neuromorphic circuits can also be used. Currently, this field is progressing at a tremendous pace [5]. It is also conceivable (and already experimentally carried out) to use living neuronal cell cultures to control real robots. These cultures could also be used to control simulated robots.

2 Neurorobotics as a New Key Technology for Neuroscience and Artificial Intelligence

Depending on the concrete form of the overall system consisting of a brain and body model, neurorobotics enables the investigation of new research questions in neuroscience as well as in artificial intelligence that previously could not be addressed with traditional approaches of the respective disciplines:

- In neuroscience, neuro-robots can be used to verify/falsify hypotheses on a real or simulated system with reproducible behaviour. This includes, for example, studies on motor skills, motion and gait control, sensor skills, action planning and selection, learning and memory as well as independent exploration. The influence of growth (ontogenesis) or ageing on the development of individual cognitive skills could also be of particular interest. Since it is not foreseeable that technical systems will grow physically over time (or age accordingly), this is a field for highly interesting simulations. In the long term, it is conceivable to replace at least simple animal experiments with the necessary software tools and high-performance computers based on biological data sets.
- In artificial intelligence, neurorobotics for the first time establishes a sound interface for the systematic transfer of knowledge from basic neuroscientific research to practical AI models. For example, new brain models that have been successfully tested in a simulated biological body model can be evaluated on an assembly line using the same tools on a jointed-arm robot. Cross-application compatible models and protocols allow the abstraction from the technical infrastructure and the focus on relevant scientific questions such as the identification of relevant principles that can be used to control the technical system. Since even the latest methods from the field of artificial intelligence and machine learning have considerable limitations in terms of learning ability, efficiency and robustness compared to the brain, this approach seems particularly promising. The embedding of a cognitive model in a body that can actively interact with its environment also enables methodological progress in established AI models and learning procedures. So far, these systems have been developed primarily for static time-invariant data sets and can therefore only be used with great effort in robotics or other cognitively oriented products. Simulations in this area in particular could considerably accelerate research.

From a broader perspective, neurorobotics enables systematic, reproducible research on any type of embodied system that is comprised of some form of cognitive model that interacts with a real or virtual environment through a body. The complexity of the model is irrelevant - it can be as simple as a small network of only a few neurons that that are connected to the camera of a mobile robot and control its wheels based on the amount of light of a certain colour in the captured image. While neurorobotics is the key to mastering the complexity of research in embodied systems, the systems themselves can range from a simple mobile robot (as just described) to a large-scale, brain simulation that controls an accurately simulated biological body model (e.g. of a mouse) with hundreds of muscles and soft tissue. The actual complexity of the system arises not only from the underlying models, but also from their closed-loop interactions that develop over time in the course of a neurorobotics experiment.

3 Research and Application Areas of Neurorobotics

In order to advance research – also in the direction of establishing future "value streams" – interdisciplinary centres of cooperation between different institutions can be established with, for example, the following orientations:

- **Closed Loop Neuroscience**: the aim here is to carry out neuroscientific research. This involves embedding a body with a nervous system that has been modelled as precisely as possible in an environment and the interaction between the two takes place in or near real time. The "brain" controls a body, which in turn can influence and change the real environment: Perception – Cognition – Action. The closure of this chain is so far only possible to a very limited extent in animal or human experiments, with all the known difficulties. If this embodiment can be done by neuro-robots, experiments can be replicated and parallelized at any scale. This will considerably accelerate progress in both fields.
- **Virtualized Brain Research**: the basis here is the modelling approach of neurorobotics including the reference to the environment and the interaction. This can be extended to general questions of neuroscience that go beyond robotics. The aim is to develop computer models for all aspects of biological models and their calibration with the help of real data. The starting points for this are neuroscientific research including computational neuroscience or experiments in closed-loop neuroscience. This will enable complex neuro- and cognitive science experiments to be "reconstructed" in computers and made available as software tools for brain research. This approach can also be applied to humans and humanoid avatars, which could, for example, enable research on degenerative brain diseases.
- **Brain-Derived Products**: for the preparation of commercially viable products, it is necessary to raise the findings from (virtual/closed-loop) brain research to a technical level at which these can be easily adopted by industrial companies and quickly transformed into new product categories of "brain-derived products". These will enable completely new control systems that achieve robustness and adaptability far beyond today's algorithmic approaches – possibly so far that these control systems will actually compete with biological systems.
- **Embodied AI/Embodied Machine Learning**: until now, methods for machine learning have been developed largely without taking into account the effects of embodiment, i.e. the interaction between physical artefacts and their real environment. However, this is currently changing. The automotive industry in particular

is very interested in so-called deep reinforcement learning for future robot vehicles, which can establish this connection. If it is possible to develop a body-related AI that has high learning rates, generalises well and produces different types of behaviour, this could lead to considerable disruptions in entire industries – not least in robotics itself: Think, for example, of the virtual prototyping of neurorobots, which could then be built as real machines that operate exactly as their virtual prototypes. This would not only accelerate robot development by orders of magnitude but could also significantly improve the testing and verification of their behaviour under a wide range of conditions.

- **Novel computational substrates**: new computational paradigms, such as neuromorphic computing and quantum computing will require new ways of programming that will be fundamentally different from traditional programming languages for von Neumann computers. Neurorobotics is a unique use case for these technologies, since it does not build on a specific set of programming and design tools. Instead, the programming of the underlying computational substrate, be it via learning or any other self-organizing mechanism, is at the core of neurorobotics experiments. Potentially, both neuromorphic computing and quantum computing can therefore substantially benefit from exploring neurorobotics use cases right from the beginning. Successful implementations of novel principles and demonstrators will, at the same time, directly yield value for robotics as a field of research and an industry as a whole because the favourable properties of neuromorphic computing and quantum computing (e.g. high energy efficiency, unprecedented computational power) are of major relevance for many applications in robotics.

The common goal of such interdisciplinary centres is the establishment of neurorobotics as a research methodology with an efficient technical infrastructure that directly serves the identified areas of application in their implementation in industry.

4 New Opportunites for AI Research and Development in Germany

The progress made in the field of massive application of artificial intelligence in China and the USA in recent years has clearly shown that the availability of suitable computer technology and corresponding application libraries is absolutely crucial for both research and industry. The enormous investments in the USA and China in research, development and practical applications in close cooperation of research and industry have led to these countries dominating the artificial intelligence market today. Neurorobotics, on the other hand, as the next step towards more efficient AI procedures and a new methodology for neuroscience, is a largely unoccupied field that is rapidly gaining international importance. This is not least due to current efforts in the field of neuromorphic processors in research (such as the SpiNNaker and BrainScaleS platforms developed with significant German participation) and industry (such as Intel Loihi, IBM TrueNorth or BrainChip Akida). While computer technology is already broadly available (neuromorphic computing) or progressing rapidly (quantum computing), methods for programming it are still lacking. This is mainly due to the fact that, unlike conventional AI methods, neuromorphic systems are not designed for processing large static data sets in data centres, but like the brain, as a model for real-time processing of dynamic data streams in embedded systems (robots, autonomous vehicles, smartphones, etc.). The emerging activities on quantum computing in Germany and Europe can benefit substantially by including neurorobotics as one of their core use cases. A close collaboration will contribute to better insight into which direction quantum computing needs to develop in order to provide value for real-world applications and can, in the future, enable neurorobotics experiments at an unprecedented level of scale.

Such systems can only be studied using neurorobotics methods, which thus become the key technology for embedded industrial AI applications.

From a scientific point of view, neurorobotics is already at a level that allows for the investigation of practically relevant questions. It is therefore important for industry to take up this topic now and gain the required momentum. Even with today's market-leading AI systems based on artificial neural networks, it is only the participation of strong industrial partners such as Google or Amazon that has led to the decisive breakthrough. Since the focus of neurorobotics is on embedded AI, which acts and learns independently without a permanent connection to the computer centre, Germany, with its strong industrial sectors such as automotive engineering, mechanical engineering and medicine, has a strategic advantage. This is because applications from these sectors are dependent on embedded real-time data processing. In order to take advantage of this fact, academic research must be put into practice as quickly as possible. This is the only way to ensure that relevant research priorities can be placed today in line with market needs and requirements. At the same time, the direct involvement of industrial partners is a prerequisite for transforming the current state of science into a sustainable competitive advantage.

5 Perspectives on Future Advancement in Germany

For Germany and German industry in particular, the window of opportunity is now to expand its currently strong position in neurorobotics through early involvement and thus to assume a leading role in the international environment.

The above-mentioned directions for the overarching research centres can be the starting point for the creation of an integrated ecosystem of research capacity (including computer technology and software infrastructure) and application-driven further development in various fields (AI methodology, (special) computer architectures, neuroscience, medicine, automotive engineering, production, etc.). Ahuge potential lies in the connection of neurorobotics with quantum computing. Germany is very competitive in these two fields of research at an international level, and can make use of this unique advantage from this synergy by following this new direction of research in early stages. In order to achieve the necessary impact and alignment of the research institutions involved and to be able to carry out initial translation and implementation measures in industry, we expect a funding volume of well over EUR 200 million for the first five years.

This technology-oriented approach is not covered by existing funding instruments, because it goes far beyond a classical research project in terms of time horizon and scope. Rather, a new funding instrument is required which, on the one hand, ensures the long-term development of the infrastructure (via the aforementioned centres) and, at the same time, promotes its active use in research and industry (e.g. via short-term funded project partners). As a starting point for the rapid development of a suitable instrument for this scenario, elements of the concept of the BMBF's research infrastructures (FIS), for example, are suitable for structuring the activities affecting the research institutions, while elements of the BMWi-funded "real laboratories" would be attractive for the implementation-oriented parts that are more concerned with industry.

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